Cryocooled Sapphire Oscillator with Ultrahigh Stability

Rabi T. Wang and G. John Dick

***Abstract*— We present test results and design details for the first short-term frequency standard to achieve ultrahigh stability without the use of liquid helium. With refrigeration provided by a commercial cryocooler, the compensated sapphire oscillator (10 K CSO) makes available the superior short-term stability and phase noise performance of cryogenic oscillators without periodic interruptions for cryogen replacement. Technical features of the 10 K CSO include use of a two-stage cryocooler with vibration isolation by helium gas at atmospheric pressure, and a new sapphire/ruby resonator design giving compensated operation at 8K to 10 K with $Q = (1-2) \times 10^9$. Stability of the first unit shows an Allan deviation of $\sigma_y \leq 2.5 \times 10^{-15}$ for measuring times of 200 s $\leq \tau \leq$ 600 s. We also present results showing the capability of the 10 K CSO to eliminate local oscillator degradation for atomic frequency standards. Configured as local oscillator (L.O.) for the LITS-7 trapped mercury ion frequency standard, the CSO/LITS combination demonstrated a limiting performance of $3.0 \times 10^{-14}/\tau^{1/2}$, the lowest value measured to date for a passive atomic frequency standard, and virtually identical to the value calculated from photon statistics.**

***Index Terms*— Cryogenics, frequency stability, microwave oscillators, sapphire.**

I. Introduction

CRYOGENIC oscillators operating below about 10 K offer the highest possible short-term stability of any frequency sources [1]–[3]. However, their use has so far been restricted to research environments due to the limited operating periods associated with liquid-helium cooling.

We have developed a cryogenic sapphire oscillator for ultrahigh short-term stability and low-phase noise in support of the Cassini Ka–band Radio Science experiment [1]. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} (1 s $\leq \tau \leq$ 100 s) and a phase noise of -73 dBc/Hz at 1 Hz measured at 34 GHz. Installation of these oscillators in stations of NASA's Deep Space Network (DSN) is planned for the years 2000 to 2002.

Continuous long-term operation is crucial to the applicability of short-term frequency standards since they are typically used to "clean up" the short-term variations of a longer term atomic standard, the combined output being then distributed to various users. Furthermore, the cryogenic oscillators can provide local oscillator (L.O.) performance as required by a new generation of passive atomic standards. These include the cesium fountain and trapped ion standards which are under development at many laboratories around the world, and the potential of which is presently thwarted by the lack of available L.O. performance [4]–[6]. Continuous operation of the L.O. is crucial to the utility of these atomic standards.

Our development was enabled in part by a new generation of two-stage Giffard–McMahon (GM) cryocoolers which allow operation at temperatures down to 4.2 K[1]. Previously, such temperatures could only be achieved by the use of an additional Joule–Thompson expansion stage, with increased complication and cost, and with reduced reliability due to the likelihood of clogging the small expansion leak.

Any cryocooler generates vibrations which, if coupled to a high-Q electromagnetic resonator, would degrade its frequency stability. However, a technology has been developed that allows isolation of cryocooler vibrations from an experiment while providing adequate cooling. In the face of very stringent vibration requirements, the experimental Mössbauer community has successfully adopted a methodology that transfers heat to cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas [7].

Cryogenic standards have used both superconducting and sapphire resonators to achieve the $Q > 10^9$ required for 1×10^{-15} frequency stability. Superconducting resonator Q's degrade to unacceptable values above about 2 K. Q's of a billion have been previously measured in whispering gallery sapphire resonators at temperatures up to 10 K [8][2]. However, the temperature sensitivity of sapphire resonators is so large that high stability can only be attained near a preferred turnover temperature where the slope of frequency versus temperature approaches zero. If sapphire turnover temperatures could be raised from typical as-supplied values of 5 K to 6 K to a reproducible 8 K to 10 K, a practical cryocooled standard with 1×10^{-15} stability could be built.

The actual value of the turnover for any given resonator depends on the concentration of incidental ($\approx$1 μg/g) paramagnetic impurities as well as the properties of the electromagnetic mode that is being excited. If impurity levels could be accurately controlled, it might be possible to construct resonators that would be compensated in the relatively narrow temperature band between that which can be achieved with

Manuscript received July 2, 1998. This work was carried under contract with the National Aeronautics and Space Administration.

The authors are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (e-mail: rwang@horology.jpl.nasa.gov).

Publisher Item Identifier S 0018-9456(99)02866-1.

[1] Balzers KelCool 4.2GM Cryocooler from Leybold Vacuum Inc., Cryogenics Div., Hudson, NH 03051-4914.

[2] HEMEX sapphire from Crystal Systems, Salem, MA 01970.

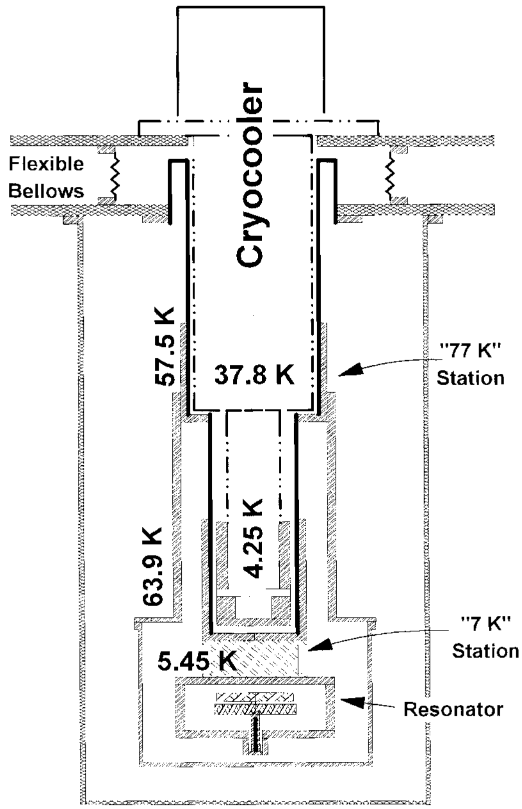

Fig. 1. Cryogenic and vibration isolation systems showing measured temperatures. A small dewar fits closely around the cryocooler with the space between them filled with helium gas at atmospheric pressure.

available cryocooler cooling and the temperature at which the Q begins to degrade. However, a fairly large increase in impurity content is required because of a weak (fifth root) dependence of turnover temperature on concentration [1]. And, this must be accomplished without degrading the resonator Q.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at cryogenic temperatures. A resonator with a mechanical compensation scheme demonstrated a stability of better than 1×10^{-13} at a temperature above 77 K [9], and combined sapphire–rutile resonators have also been investigated [10]. However, the Q values of a million or so that are so far achievable with these schemes are far below those needed.

II. Design Aspects

Cryogenic aspects of design are shown in Fig. 1 and have been presented previously [1]. The cryocooler is mounted as rigidly as possible to the floor and the cryostat assembly is independently supported from the floor using conventional vibration isolation components.

Cryogenic systems providing vibration isolation by means of helium gas conduction are available commercially based on small 7 K two-stage G-M cryocoolers. However, the available performance for these units is limited to temperatures above 13 to 15 K, using a patented thermal design. Based on our calculations of thermal conduction by turbulent gas flow, we conclude that a simple design with a gap of a few millimeters between concentric cylinders shows higher thermal conductivity for any given geometrical constraint than the patented designs [11].

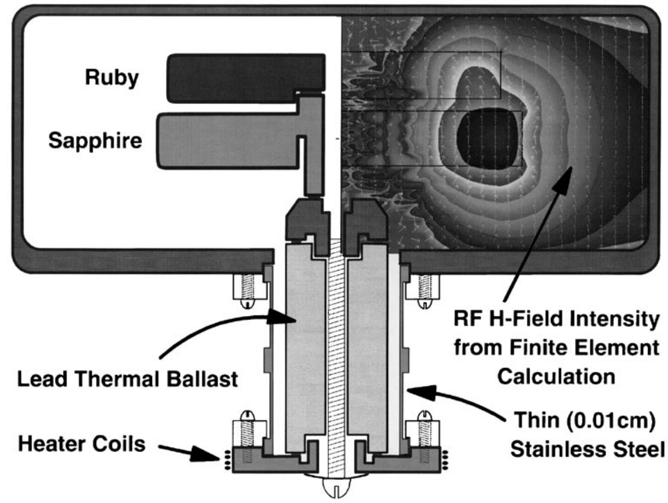

Fig. 2. Compensated sapphire resonator showing details of electromagnetic and thermal design. The thin-walled stainless steel tube thermally isolates the resonator elements while providing good RF confinement. Electromagnetic field intensity varies approximately one order of magnitude per color band as calculated by the CYRES-2 finite-element computer program.

The resonator design shown in Fig. 2 compensates the frequency variation of a whispering-gallery sapphire resonator by means of a proximate and thermally attached ruby element. The high chromium concentration in the ruby gives a large compensation effect that can be reduced by adjusting its position. The ruby was constructed so as to allow assembly gaps of either 2 or 4 mm between ruby and sapphire elements.

A $\mathrm{WGE}_{14,1,1}$ quasi-TE mode was chosen to minimize the size of the copper shielding container while still allowing a shield-limited Q of greater than 10^{10}. With significant axial H-fields, the WGE mode also facilitates coupling to a ruby element displaced axially from the sapphire. An operating frequency of 10.4 GHz was chosen to give effective spin-tuning without excessive losses. Finite element calculations were used to calculate energy in the ruby element and its diameter was adjusted to give the desired ≈0.12% energy content [12].

Compensation design involves balancing the Debye expansion ($\propto T^4$) by a $1/T$ spin-dependent term. The sign of the spin term is appropriate for compensation for frequencies below the 11.44 GHz zero-field splitting. Microwave coupling to the spins depends on the geometry of the resonator and the electromagnetic mode—the WGE mode excited in the sapphire does not couple to the spins. This gives resonator baseline behavior without a temperature turnover, and thus avoids the variability of spin-tuning from sample to sample in even the best sapphire. A rotation of the magnetic field orientation from the vertical in the ruby is observable in Fig. 2 and provides effective coupling to the ruby spins.

Finally, ruby spin-tuning values are required to calculate the ruby electromagnetic energy requirement given above and the spin-loss values will place a limit on Q, and on the loss of Q

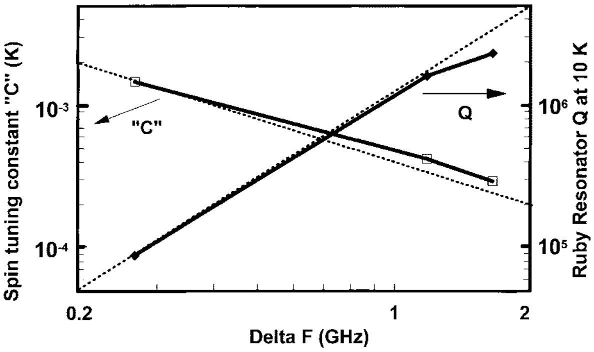

Fig. 3. Measured reactive and resistive components for the permittivity of 0.03 splitting for chromium impurities in ruby. Together, these two curves allow the spin-limited Q to be calculated for any ruby–sapphire compensated resonator. The dotted lines show slopes of -1 and $+2$ as predicted by the Lorenzian model.

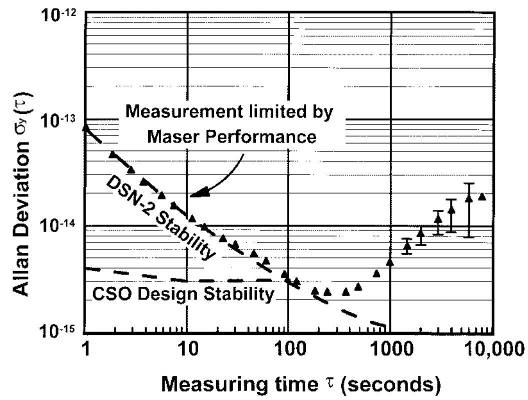

Fig. 5. Measured frequency stability for the 10 K CSO against a DSN-2 hydrogen maser tuned for best short-term stability. Even this "hot" H-maser reference dominates the observed short term variation. The long-term turn-up is due to the CSO and is likely caused by sensitivity of the RF electronics to room temperature variations.

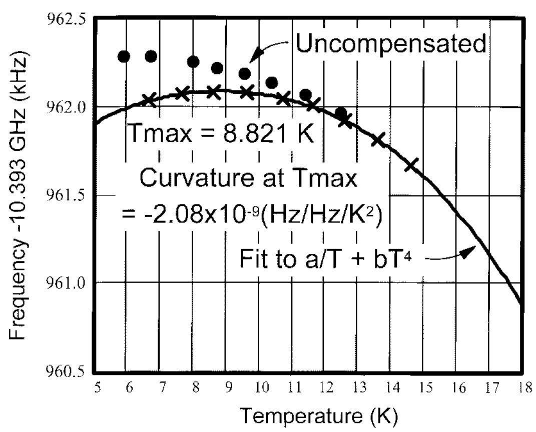

Fig. 4. Measured temperature dependence of the compensated resonator with a 4 mm spacing between sapphire and ruby elements. This resonator shows a turnover temperature of 8.821 K compared to the predicted value of 7.43 K shown in Fig. 2.

with increasing turnover temperature [13]. Our measurements of the characteristics of a 0.03% g/g ruby sample are shown in Fig. 3 and have been confirmed with measurements of five more samples. For our operation, 1 GHz below the zero-field splitting, we calculate a spin-loss limiting Q of about 3×10^9.

III. Experimental

Fig. 4 shows the first reported frequency turnover for a resonator with adjustable compensation and ultrahigh Q. The turnover temperature at 8.821 K for the first assembly is close to the calculated value of 7.25 K. The Q of the first sapphire was about 300 million at 8 K to 10 K with or without the ruby compensating element. The mode excited is $\mathrm{WGE}_{14,1,1}$ at 10.395 GHz.

Frequency stability tests were performed with and without the ruby compensation element. Even without compensation, the thermal ballast removes short-term variations, showing a random-walk type stability of approximately $3 \times 10^{-15} \times \tau^{1/2}$, observed for measuring times above about 30 s. Based on our thermal analysis, we expect the short-term behavior to improve as $1/\tau$ for measuring times longer than 0.8 s, the ruby-sapphire thermal response time. This would give a stability of less than 1×10^{-15} for measuring times $\tau \geq 10$ s.

Compensated stability tests with the first resonator assembly showed a flicker floor of about 7×10^{-15}. We have not yet determined if the floor was due to the somewhat low resonator Q or to an observed frequency pulling with RF amplitude of more than 1×10^{-11} Hz/Hz/dB.

Fig. 5 shows frequency stability measurements for the first resonator after it was sent back to the supplier for an "after-polish anneal," which had been skipped on the first two samples in order to meet our delivery schedule. The resonator as assembled the second time shows an unloaded Q of about 1×10^9 with almost exactly critical coupling. Additionally, probably due to the better coupling, the resonator showed a sharply reduced RF amplitude pulling of $\approx 10^{-12}$ Hz/Hz/dB. The turnover temperature increased slightly to 8.54 K.

The short-term part of the stability shown in Fig. 5 is limited by maser performance with no additional fluctuations attributable to the CSO. The flicker floor is below $\sigma_y = 2.4 \times 10^{-15}$.

The low 10^{-13}/day drift of the CSO allowed easy application as L.O. for the JPL linear ion trap standard (LITS) [4], [5]. Frequency pulling of $\delta\nu/\nu = 10^{-11}$ was possible by addition of an external dc voltage to the Pound frequency lock circuitry of the CSO. The LITS was tuned for high S/N and low $1/\tau^{1/2}$ fluctuations, yielding a calculated deviation for statistical (light count) variations of $3.0 \times 10^{-14}/\tau^{1/2}$.

Fig. 6 shows a comparison of the CSO–LITS standard with a SAO hydrogen maser. The measured stability is limited at all measuring times by hydrogen maser frequency fluctuations.

The significance of this demonstration is two-fold. First, use of the CSO as L.O. allows us for the first time to see the LITS stability essentially undegraded by L.O. effects [14]. Second, the coefficient of the $1/\tau^{1/2}$ slope is the lowest measured to date for a passive microwave atomic frequency standard, complementing previous demonstrations of exceptional stability of the LITS for measuring times of thousands of seconds to weeks and months [5].

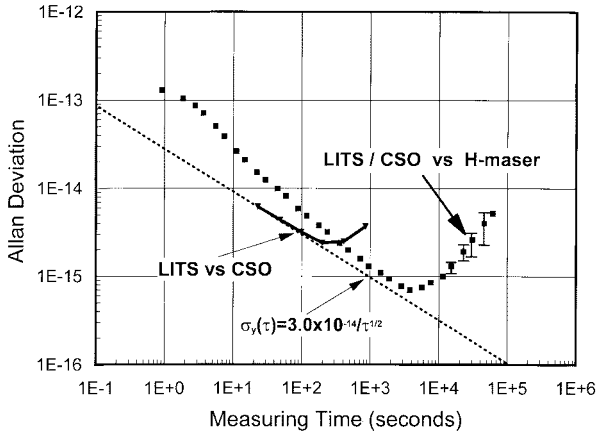

Fig. 6. Comparison of the combined LITS/CSO to an SAO H-maser with excellent long-term stability. The LITS versus CSO data is obtained by time analysis of the feedback signal to the frequency-locked CSO for shorter time scales where the CSO has the superior stability. This work represents the first demonstration in our laboratory of any other standard that equals or betters this hydrogen maser for all measuring times.

IV. Conclusions

The 10 K compensated sapphire oscillator has been demonstrated as the first continuously operable frequency standard with ultrahigh short term stability. Phase noise tests are being addressed with construction of a second unit which should be operational within a few months. Stability is clearly superior to the hydrogen maser at short measuring times, and we expect to meet the requirement of $(3–4) \times 10^{-15}$ stability for 1 s $\leq \tau \leq$ 100 s for the CASSINI Ka-band experiment. Phase noise measurements are expected soon with the completion of a second unit.

Freed of the limitations of quartz or hydrogen maser L.O.'s the new generation of passive atomic standards such as the LITS and cesium fountain can now be operated continuously while realizing their inherent capabilities. A local oscillator with the capability of the 10 K CSO can enable these standards to achieve stabilities of better than $1 \times 10^{-14}/\tau^{1/2}$.

References

[1] J. Dick and R. T. Wang, "Cryocooled sapphire oscillator for the CASSINI Ka-band experiment," in *Proc. 1997 Int. IEEE Frequency Control Symp.*, 1997, pp. 1009–1014.

[2] ——, "Improved performance of the superconducting cavity maser at short measuring times," in *Proc. 44th Annu. Frequency Control Symp.*, 1990, pp. 89–93.

[3] A. N. Luiten, A. G. Mann, N. J. McDonald, and D. G. Blair, "Latest results of the U. W. A. cryogenic sapphire oscillator," in *Proc. 1995 Int. Frequency Control Symp.*, 1995, pp. 433–437.

[4] R. L. Tjoelker, C. Bricker, W. Diener, R. L. Hamell, A. Kirk, P. Kuhnle, L. Maleki, J. D. Prestage, D. Santiago, D. Seidel, D. A. Stowers, R. L. Sydnor, and T. Tucker, "A mercury ion frequency standard engineering prototype for the NASA deep space network," in *Proc. 1996 Int. Frequency Control Symp.*, pp. 1073–1081.

[5] R. L. Tjoelker, J. D. Prestage, and L. Maleki, "Record frequency stability with mercury in a linear ion trap," in *Proc. 5th Symp. Frequency Standards Metrology*, Woods Hole, MA, Oct. 15–19, 1995.

[6] G. Santarelli, S. Ghezali, Ph. Laurent, S. N. Lea, M. Bahoura, K. Szymaniec, E. Simon, and A. Clairon, "Recent results of the LPTF cesium fountain primary frequency standard," in *Proc. 1995 IEEE Int. Frequency Control Symp.*, pp. 60–65.

[7] P. Boolchand, G. H. Lemon, W. J. Bresser, R. N. Enzweller, and R. Harris, "A general purpose cold finger using a vibration-free mounted He closed-cycle cryostat," *Rev. Sci. Instrum.*, vol. 66, pp. 3015–3057, Apr. 1995.

[8] A. G. Mann, A. N. Luiten, D. G. Blair, and M. J. Buckingham, "Ultra-stable cryogenic sapphire dielectric microwave resonators," in *Proc. 46th Annu. Frequency Control Symp.*, 1992, pp. 167–171.

[9] D. G. Santiago, G. J. Dick, and R. T. Wang, "Frequency stability of 1×10^{-13} in a compensated sapphire oscillator operating above 77 K," in *Proc. 1996 Int. IEEE Frequency Control Symp.*, pp. 772–775.

[10] M. E. Tobar, J. Krupka, J. G. Hartnett, E. N. Ivanov, and R. A. Woode, "Sapphire-rutile frequency temperature compensated whispering gallery microwave resonators," in *Proc. 1997 IEEE Int. Frequency Control Symp.*, pp. 1000–1008.

[11] G. D. Raithby and K. G. T. Hollands, "Natural convection," in *Handbook of Heat Transfer Fundamentals*, 2nd ed., W. M. Rohsenow, J. P. Hartnett, and E. N. Ganic, Eds. New York: McGraw-Hill, 1985.

[12] R. A. Osegueda, J. H. Pierluissi, L. M. Gill, A. Revilla, G. J. Villalva, G. J. Dick, D. G. Santiago, and R. T. Wang, "Two-dimensional finite element determination of modes and frequencies for an anisotropic cylindrical dielectric resonator," in *Proc. 10th Annu. Review Progress Applied Computational Electromagnetics (ACES)*, 1994.

[13] P. H. Ceperly and J. G. Castle, Jr., "UHF losses in sapphire and ruby at low temperatures," *IEEE Trans. Nucl. Sci.*, vol. NS-19, pp. 222–225, 1972.

[14] G. J. Dick, "Local oscillator induced instabilities in trapped ion frequency standards," in *Proc. 19th Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, Redondo Beach, CA, 1987, pp. 133–147.

Rabi T. Wang was born in Taiwan, R.O.C., on December 18, 1956. He received the B.S. degree in physics from Tunghai University, Taiwan, and the M.S. and Ph.D. degrees in cryogenic physics from the University of Oregon, Eugene, in 1983 and 1987, respectively.

From 1987 to 1989, he was a Resident Research Associate with the National Research Council, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, performing research on superconducting cavity mase oscillators. Currently, he is a Member of the Time and Frequency Systems Research Group, Jet Propulsion Laboratory.

Dr. Wang is a member of the American Physical Society.

G. John Dick was born in Ohio in 1939. He received the A.B. degree in physics and mathematics from Bethel College, North Newton, KS, in 1961 and the Ph.D. degree in physics from the University of California, Berkeley, in 1969. His Ph.D. dissertation was a study of the effects of magnetic impurities on millimeter wave absorption in superconducting films.

After a postdoctoral research fellowship at California Institute of Technology, Pasadena, he joined the research faculty as Senior Research Fellow, developing RF resonator technology for superconducting accelerator applications. During 1979 and 1980, he was a Visiting Faculty Member, State University of New York, Stony Brook. In 1986, he transferred to the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, where he presently serves as Scientist and Research Manager, Time and Frequency Research Group, operating in support of the Deep Space Network. His research interests include microwave and RF resonator and resonator coupling design, ultrastable and ultralow-noise oscillator systematics, and microwave conductivity in normal and superconducting metals.